

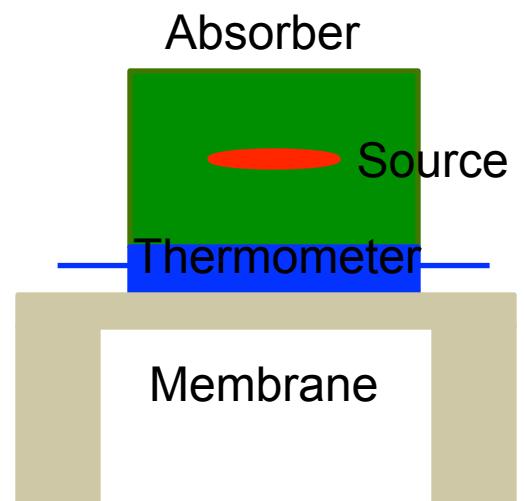
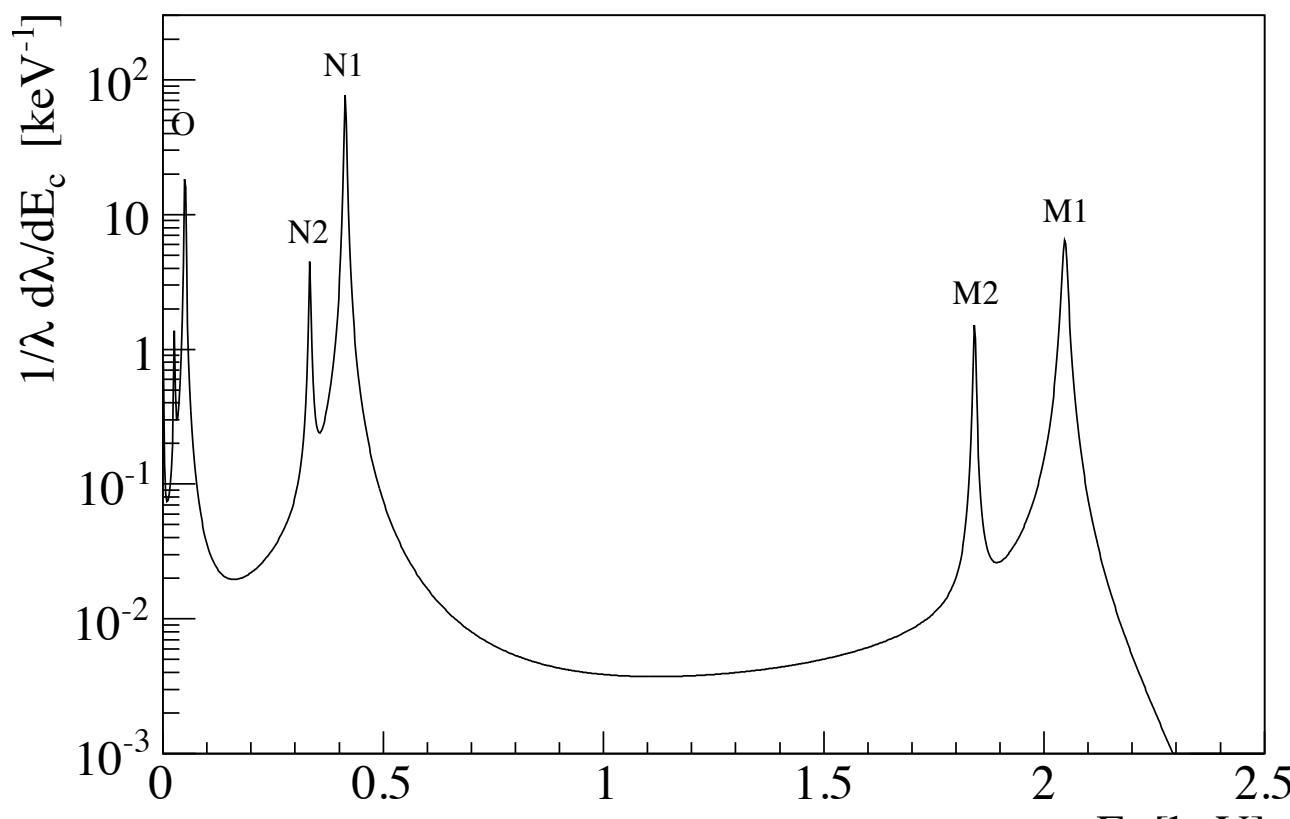
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# Measuring the Neutrino Mass with Cryogenic Microcalorimeters

*Massimiliano Galeazzi*  
University of Miami

# Ho-163 Electron Capture Decay



$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2} (Q - E_c) \sqrt{(Q - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

# How to design a Ho Experiment

- Understanding the decay

- Reaction Q-value

- Tasks to address

- Ho-163 Production

- Source Deposition

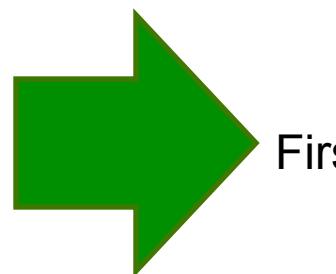
- Detector Performance

- Current efforts

- HOLMES

- ECHO

- NuMECS



First Step ~1,000 detectors  
< 1 eV/c<sup>2</sup> sensitivity

} ~5 years



Scalable to 10,000-100,000 detectors  
<0.1 eV/c<sup>2</sup> sensitivity

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# Q-Value

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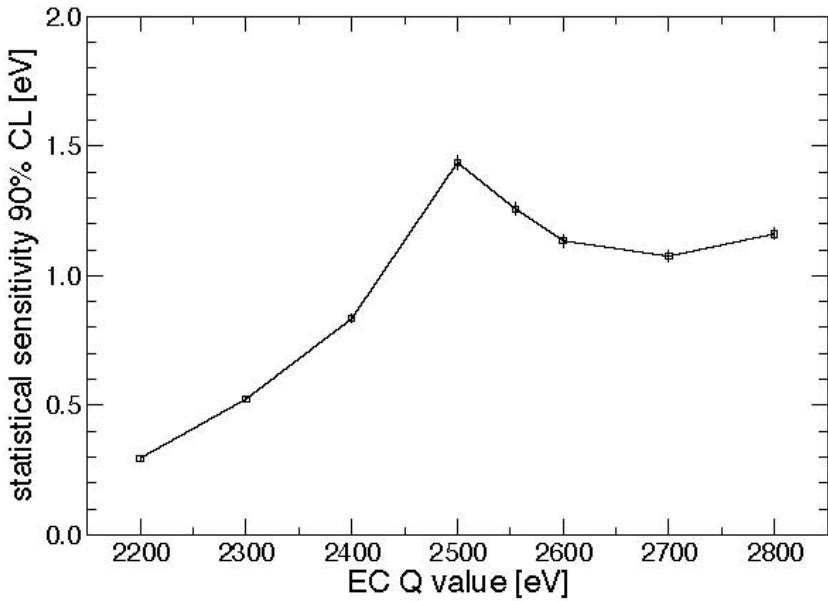
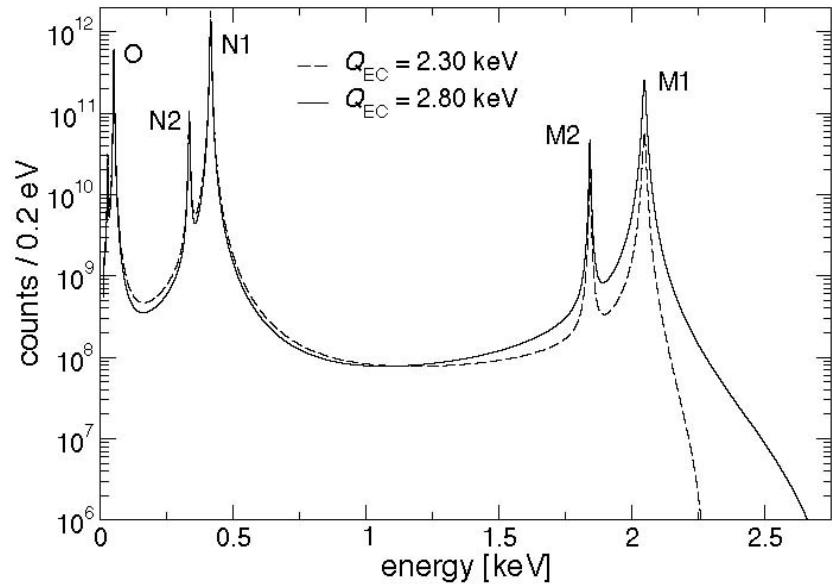


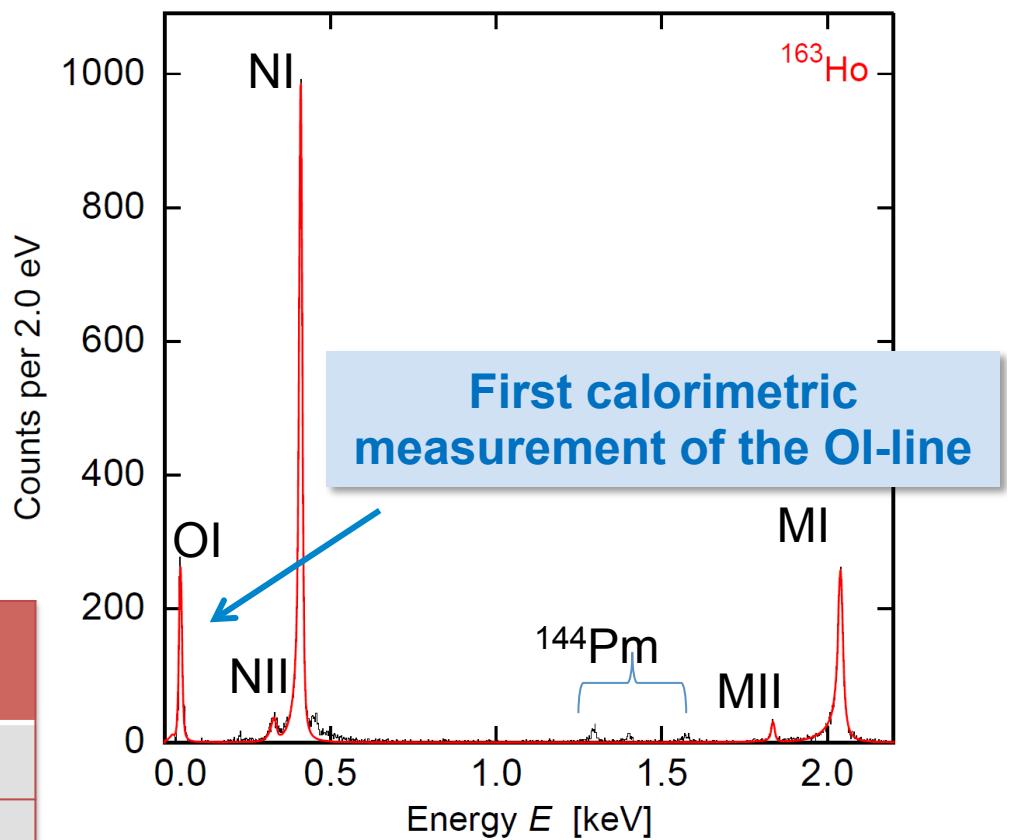
Table 2: Experimental exposure required for various target statistical sensitivities, with  $b = 0$  and two different sets of detector parameters. Configuration A is with  $\Delta E_{FWHM} = 1 \text{ eV}$ ,  $\tau_R = 1 \mu\text{s}$  and  $A_\beta = 1000 \text{ Hz}$ . Configuration B is with  $\Delta E_{FWHM} = 0.3 \text{ eV}$ ,  $\tau_R = 0.1 \mu\text{s}$  and  $A_\beta = 10000 \text{ Hz}$ .

$Q$ [eV]	target sensitivity [eV]	exposure $T$ [detector×year]	
		Conf. A	Conf. B
2200	0.2	$2.6 \times 10^4$	$3.3 \times 10^3$
2200	0.1	$4.1 \times 10^5$	$4.8 \times 10^4$
2200	0.05	$6.6 \times 10^6$	$7.7 \times 10^5$
2800	0.2	$6.5 \times 10^6$	$6.3 \times 10^5$
2800	0.1	$1.0 \times 10^8$	$1.0 \times 10^7$
2800	0.05	$1.7 \times 10^9$	$1.6 \times 10^8$

# ECHo: Calorimetric spectrum

- Rise Time  $\sim 130$  ns
- $\Delta E_{\text{FWHM}} = 7.6$  eV @ 6 keV (2013)  
 $\Delta E_{\text{FWHM}} = 2.4$  eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise  $^{163}\text{Ho}$  spectrum

	$E_{\text{H}}$ bind.	$E_{\text{H}}$ exp.	$\Gamma_{\text{H}}$ lit.	$\Gamma_{\text{H}}$ exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3



$$Q_{\text{EC}} = (2.843 \pm 0.009^{\text{stat}} - 0.06^{\text{syst}}) \text{ keV}$$

P. C.-O. Ranitzsch et al., <http://arxiv.org/abs/1409.0071v1>  
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

# Q-Value

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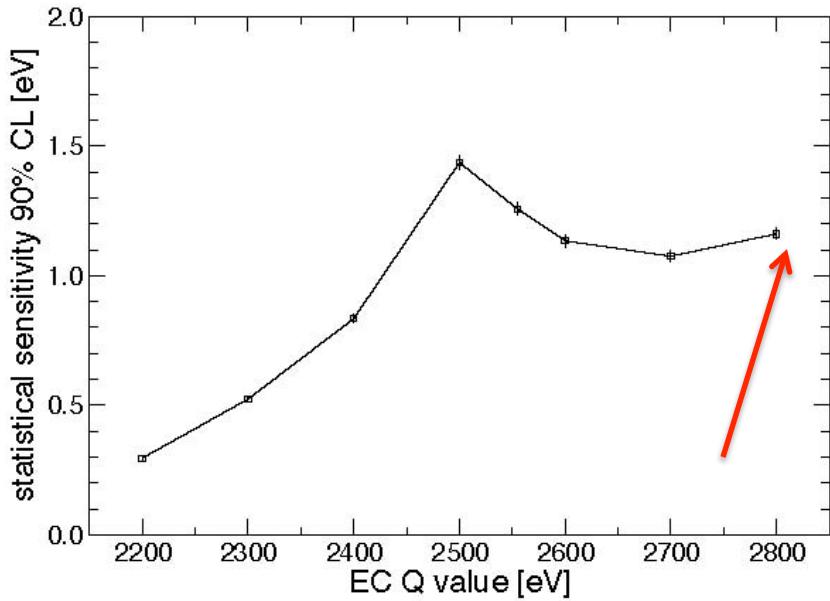
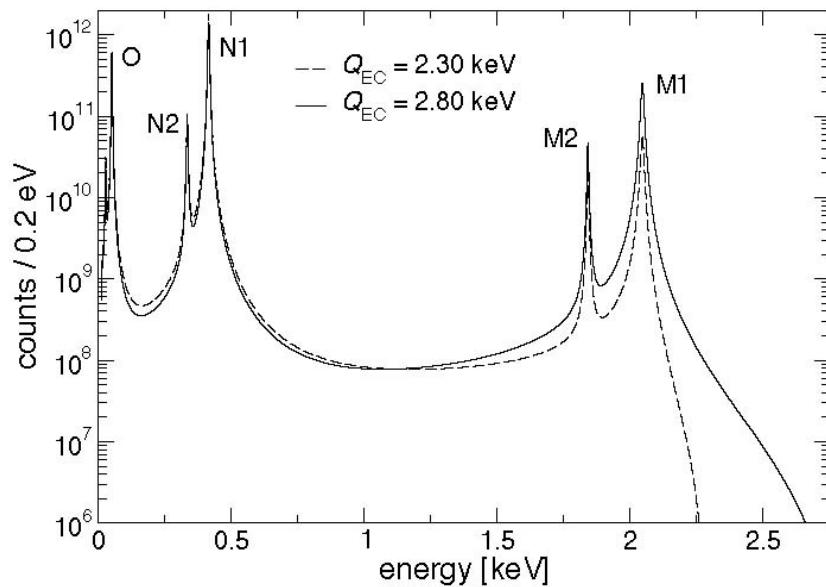


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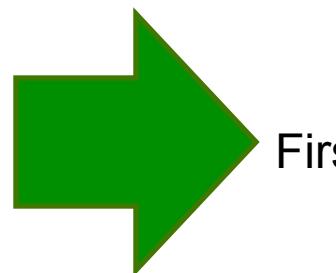
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# Ho-163 production and purification

HOLMES

ECHo

NuMECS

neutron activation in nuclear reactor of  $^{162}\text{Er}$   
 $[^{162}\text{Er}(\text{n},\gamma)^{163}\text{Er}(75\text{min}) \rightarrow ^{163}\text{Ho}]$

neutron  
irradiation of  
 $\text{Er}_2\text{O}_3$  enriched  
in  $^{162}\text{Er}$  @ ILL,  
Grenoble,  
France

alpha particle bombardment of  $^{165}\text{Ho}$  target  
 $[^{165}\text{Ho}(4\text{He},^*)^{163}\text{Ho}]$

proton bombardment of natural dysprosium  
 $^{nat}\text{Dy}(\text{p}, \text{xn})^{163}\text{Ho}$

Comprehensive investigation of all  
methods

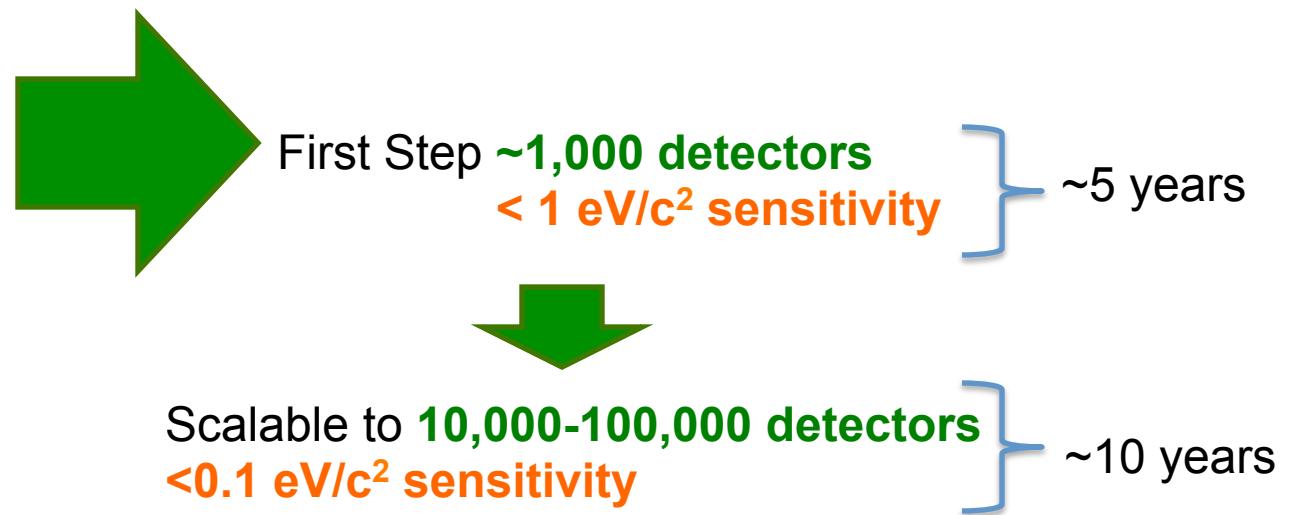
Focus on  
proton  
irradiation @  
LANL to  
reduce  
byproducts

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# How to design a Ho Experiment

- Understanding the decay
  - Reaction Q-value
- Tasks to address
  - Ho-163 Production
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  - Detector Performance
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# Embedding the source in the absorber

Two issues to address:

- ◆ Waste of radioactive material in the process (limited supply of  $^{163}\text{Ho}$ )
- ◆ Effect of the source on the microcalorimeter performance

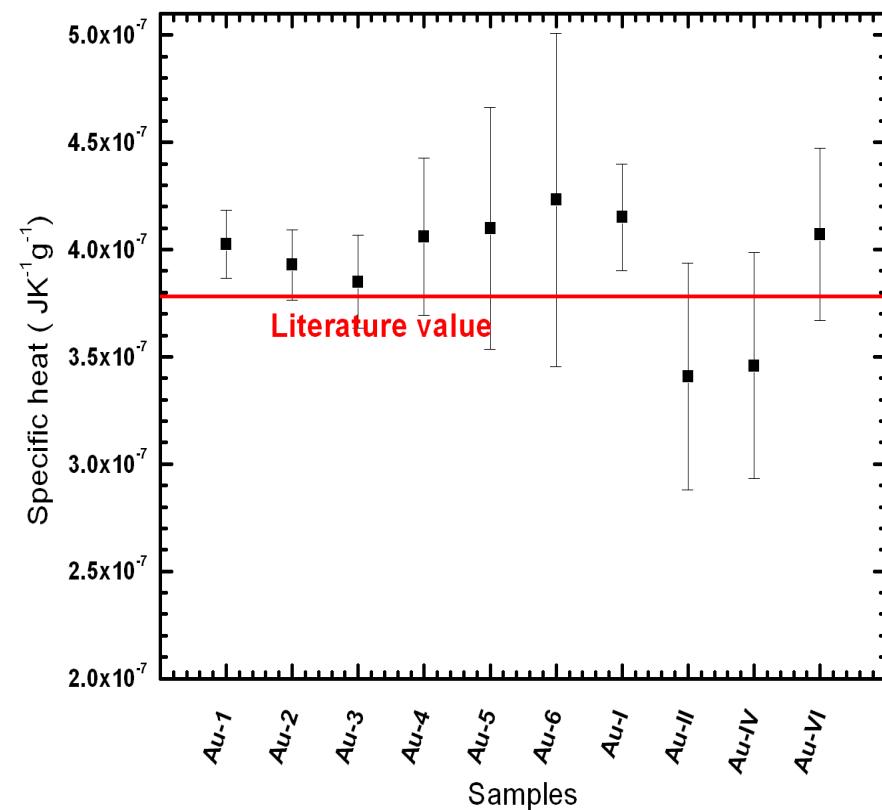
HOLMES: high-temperature vacuum reduction and distillation technique and is building a custom mass separator ion implanter

ECHo: mass separation and ion implantation at ISOLDE (CERN)

NuMECS: pico-liter deposition technology, surface chemistry and interface metallurgy

# Effect of Implanted Ho on thermal properties of absorber

Implanted ion concentrations ( $\text{cm}^{-2}$ )				
Samples	$\text{Ho}^+$ (180KeV)	$\text{Ho}^+$ (250KeV)	$\text{Er}^+$ (180KeV)	$\text{Er}^+$ (250KeV)
Au-I				
Au-II	$4 \times 10^{15}$			
Au-IV	$4 \times 10^{15}$		$9.6 \times 10^{15}$	
Au-VI			$9.6 \times 10^{15}$	
Au-1	$4 \times 10^{15}$	$8 \times 10^{15}$		
Au-2		$8 \times 10^{15}$		
Au-3	$4 \times 10^{15}$	$8 \times 10^{15}$	$9.6 \times 10^{15}$	$1.9 \times 10^{16}$
Au-4		$8 \times 10^{15}$		$1.9 \times 10^{16}$
Au-5			$9.6 \times 10^{15}$	$1.9 \times 10^{16}$
Au-6				$1.9 \times 10^{16}$



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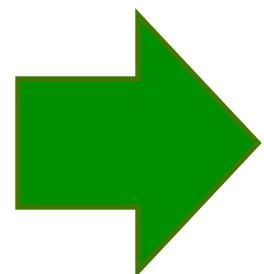
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# Detector Development

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## Detector technology:

Transition Edge Sensors (TES)

Magnetic Microcalorimeters (MM)

Magnetic Penetration Thermometers  
(MPTs)

## Multiplexing:

Time Domain

Frequency Domain

Microwave



# Detector Development

	Short term readiness	Pile-up limited	Maximum Count rate	Number of channels
<b>Detector technology:</b>				
<b>Multiplexing:</b>				

# Conclusions

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**What is the ultimate reach of each approach, and on what timescale?**

- ✓ < 1 eV/c<sup>2</sup> in the short term (~3-5 years)
- ✓ < 0.1 eV/c<sup>2</sup> in the longer term (~10 years)
- ✓ No intrinsic limit to the sensitivity

**For experiments in the concept/proposal stage: what R&D is required to demonstrate the ultimate sensitivity?**

- ✓ Short term goals: source production and purification on large scale, embedding of Ho source, storage and data analysis
- ✓ For long term goals, microwave multiplexing, MPTs, improvements on current techniques

**Are there any technological advances that can be leveraged to improve the sensitivity by another one or two orders of magnitude beyond KATRIN and on what timescale?**

Microcalorimeter detectors and multiplexing are developed for astrophysics and other fields

**Is availability of isotopes an issue?** Maybe, but issue is being addressed

